Draft notes on SDO as observer coordinates (30 November 2020 version, PHS)

Contents:

Pending change in SDO/JSOC metadata, some action needed by users.

We will soon make a change in the calculation of Carrington and Stonyhurst longitude of the solar disk center as seen by SDO. This change effects both HMI and AIA data. This change corrects a long-standing net offset error of **0.081894** degrees in the keyword CRLN_OBS and up to 0.015 degrees errors in Stonyhurst longitude which was not provided beyond level-1 data.

You may need to make software changes to accommodate the keyword changes which will be implemented on 3 December 2020 for science level data starting 29 November 2020. The c. 0.08 degree change in the solar longitude of disk center as seen from SDO amounts to about 2.7 HMI pixels and 2.3 AIA pixels at disk center. If you use the CRLN_OBS in FITS or DRMS keywords to select regions to track as the Sun rotates you will see a jump of 2.7 or 2.3 pixels in data for the time that the correction is made. The CRLN_OBS correction is a constant offset. If you use the AIA Stonyhurst HGLN_OBS keyword, it will change from always 0.0 degrees to a correct value with a 24-hour period with amplitude about 0.015 degrees, a bit less than half a pixel. For HMI and AIA an appropriate calibration version keyword will contain an indication of the change.

Notes on the changes

Details about the change:

For CRLN_OBS, the longitude of disk center as seen by the observer (SDO in this case), the change in JSOC production code will be made on 2 December for data made on 3 December. **If your code, or the code on 3rd party libraries, does not use the value of the CRLN_OBS keyword then no changes are needed.**

A calibration version keyword will have a changed value with all records created with the new code. For HMI and AIA this keyword in level-1 data is CALVER32. For all higher-level HMI data products it will be in CALVER64, a 64-bit integer. (The lower 32 bits of CALVER64 are CALVER32). The description of the meaning of "nibbles", 4-bit segments, of these keywords is found at http://jsoc.stanford.edu/jsocwiki/CalibrationVersions. The keyword is treated as 8 4-bit sections each containing a version number for a particular topic. The bit number 28, or bit 0 in the highest nibble will be set when the corrected code is used. A simple test could be:

C or Python: newvalues = (1<<28) & calver

The calibration version keyword for AIA is CALVER32, an alias for the unused keyword ROI_NWIN.

The action to take when this bit is set, or not set as is the case now, depends on the user's choices. Since all future data, and all data that is obtained from the still future NASA SDO archive, will have the new values we believe a good choice in most cases is to correct older data when using it. A sample code snippet could be, in meta-code:

If ((1<<28) & calver) == 0 then use CRLN_OBS = old CRLN_OBS – 0.081894

The net effect of the change is that if you use CRLN_OBS to locate a particular solar longitude on the Sun, it will appear to shift c. 3 pixels to the west since the reference longitude will have moved that amount to the east. Cases where this may matter are for instance in making a time series of cutout patches of a particular active region that is on the disk when the change in code is made. Another case is in the production of synoptic charts as is often used for large scale magnetic field evolution studies, although since most of those are made with reduced resolution the change will likely not matter. Yet another case could be in the reference longitude for helioseismic studies where a jump in location will look like a jump in phase of waves traveling eastward or westward. In nearly all studies, there will be no noticeable change for all analyses not including November 2020. But we advise verification of this for your studies.

Reason for the change now:

One of the primary reasons to have more accurate observer heliographic coordinates is for comparisons of data obtained from different observatories. Until recently image resolution and inaccurate location knowledge meant that analysists chose to co-align images by linking to features identifiable in each type of image. For some purposes such as helioseismology this can not be done. We will soon have much higher resolution data (e.g. DKIST) and data from far vantage points (SO) so it is our responsibility to be able to locate particular solar features in SDO data with sufficient accuracy that when other data sources have sub-arcsec location determinations direct comparisons via coordinates can be made.

Source of the error:

For the longitude correction, most of the change is from an error of not adding light travel time to 1 AU while subtracting light travel time to the observer. AU/c is about 499 seconds. In that time the coordinate system rotates 0.081922 degrees. This accounts for most of the 0.081894-degree correction. The remaining -0.000028 degree comes from several almost cancelling minor corrections described in the History section of this note. Adding 0.081894 degree to the total number of degrees the coordinate frame rotates since some past epoch results in subtracting that amount from the longitude of disk center.

For the Stonyhurst coordinates, we (JSOC) simply did not bother to calculate the values once we discovered how small they are. However, some users prefer to use them even though the maximum value of HGLN, Stonyhurst longitude of disk center, is less than 0.015 degrees, less than half a pixel. Stonyhurst longitude is defined as the location of the observes central meridian, as if seen from Earth. The maximum angle is the SDO orbit radius divided by the distance from Sun to SDO. We did include the HGLN_OBS and HGLT_OBS keywords in level-1 data but did not propagate them into higher level products for HMI. For AIA, level-1 is the final science ready product. Note that HGLT_OBS is exactly CRLT_OBS so no change is needed for it.

History of "Carrington Longitude", CRLN:

The source of the JSOC code error was from a misreading of the changes in the way that the disk center longitude should be reported that were made at the same time the code was being made and tested in 2009. Prior to about 1980 the observer's disk center longitude was specified by the number of degrees of rotation of the Sun's Prime Meridian since 1 January 1854 noon Ephemeris Time a correction for the ecliptic longitude of the Earth at the observation time. The rate of rotation was specified by Carrington in (1863) as 360 degrees per 25.38 days. The Prime Meridian is defined as the ascending node on the solar equator on the ecliptic plane at the 1854 reference time. The ecliptic plane precesses at about 0.14 degrees per century. As of the time J2000 the ascending node on the ecliptic is 75.76 + 0.01397 degrees per year.

The traditional way used by various published ephemerae has been to find the location of the Prime meridian with respect to the ascending node on the celestial sphere which centered on the Earth's equator versus the elliptic. Since we (SDO data users) know location of SDO with respect to the ecliptic from data provided in tables made by the SDO FDS (Flight Dynamics System), it makes sense to use the ecliptic reference point in J2000 coordinates rather than first converting to Earth coordinates then using the method suggested by the IAU 84.10 (1990*) or 84.18 degrees (2009) or 84.176 degrees (2011) as the ascending node of the Sun's equator along the Earth's equator.

We (JSOC code by P. Scherrer) used the original method using the ascending node on the J2000 ecliptic counting total degrees from 1854 but using the new definition of rotation rate of 14.1844000 degrees per day. This rate was adopted and described in e.g. the American Ephemeris as 14.18440 degrees per day as rounded from 360/25.38 (in about 1980?) and redefined as exactly 14.1844000 degrees (Archinal et al., 2011).

The difference 14.1844000 - 360/25.38 is about 0.001 degrees per year. Using 1980 as a convenient reference year, the correction is about 0.13 degrees to be added to disk center longitude.
As per the recommendation by the IAU in 1976 and later meetings the method of computing the solar ephemeris was changed to match that for other solar system bodies, to report the coordinates as if observed at the body. Then the observer (on Earth or some spacecraft) should subtract the number of degrees that the Sun rotated during light travel time from the Sun to observer. The changes mentioned above for reference for the prime meridian (84.10, 84.18, 84.176) was to align the new method with traditional values where it is assumed that Carrington used the coordinates as observed. The first step then is to add back in the 1 AU travel time rotation of 0.0819222 while subtracting the actual time to

observer, rounded to 0.08 degrees to get 84.18 degrees, then realizing that a) this was not accurate (should be 84.182), and b) that aberration should also be removed and left to the observer (-0.006 degrees) producing the current 84.176 value.

The final JSOC SDO correction for calculating degrees since 1854 is a change in time of c/AU of about 499 seconds and a correction for the rate change to be in sync in 1980, and a small correction to use the light starting point as the solar surface not the Sun's center (c. 696 Mm), and an adjustment to split the difference between the JPL Horizons results averaged over the first decade of SDO and the same calculation using the SunPy code (version 2.10 and above as of July 2020). The discussions and comparisons that enabled this change involved the change in the JSOC code, the SunPy code, and the precision reported by the JPL Horizons online ephemeris. (Note that JPL has SDO as an observer location specified as [500@-136395] with the accuracy fixed in XXX and again in *a few years ago* such the difference between JSOC, JPL, and Sunpy is now in the range of 1e-5 degrees for Carrington longitude and 1e-4 for latitude.
Note that 1 HMI pixel is about 0.027 degrees and AIA 0.024 degrees at disk center.

New Ancillary Series with new and more coordinates

Three new JSOC data series have been developed containing the corrected values for CRLN_OBS and HGLN_OBS as well as, for completeness, CRLT_OBS, OBS_VR, OBS_VW, OBS_VN, CAR_ROT, T_REC and new keywords deltaLT, GHGD_OBS, GHGW_OBS, GHGN_OBS. The first if these new series is ***sdo.location*** containing the above keywords at a one-minute cadence for time from before the data taking phase of the SDO mission until a week or more in the future, updated at least weekly. The FDS orbit data is available in 5-week predictions provided each week or sooner if an orbit maneuver happened. The predictions are quite good and can be used at least a week or more after the calculation dates. These values are within expected double precision errors of the existing values in exported data except for CRLN_OBS and HGLN_OBS, and the new keywords of course.

Two additional series containing the same keywords as sdo.location but calculated at the exact same times as HMI 45s and 720s data products. These series are named ***hmi.location_45s*** and ***hmi.location_720s***. In addition to the sdo.location keywords, these series include updated CALVER64 and for reference QUALITY keywords. This allows one to update data generated by the JSOC prior to 3 December 2020 with simple substitutions of CRLN_OBS and CALVER64. These series are updated a few days after the NRT products are made.

The longitude and latitude keywords have higher precision here than in the normal JSOC data series where they were/are stored as floats instead of double precision. Now that we will have 6 digits of precision and want to show the 7^{th} digit as well, floats are no longer sufficient for CRLN_OBS. The velocity data was always presented in double precision. The data is available with a 60-second cadence in TAI so no issue with leap seconds. CAR_ROT, the Carrington rotation number, is included because the change in CRLN_OBS moves the rotation number in a few cases.

For the velocity in particular, one should do at least a linear interpolation between the one-minute samples and the actual time at SDO since we want to have the velocity correction for helioseismology and other studies to be known better than 1 m/s. For the other quantities the one-minute cadence will usually be sufficient to a fraction of a pixel. But since the linear interpolation code is needed for some keywords, we suggest just doing it for all. But note that all but the longitude keywords are unchanged from the values in the JSOC DRMS and FITS headers.

The new keyword “deltaLT” is the difference in solar latitude of disk center as seen by SDO and from Earth center. This is shown for interest since when combined with HGLT_OBS shows the motion of SDO about the Earth. Positive value means SDO has higher latitude than the Earth.

The new keywords GHGx_OBS where “x” is one of “D”, “W”, or “N” contain the distance of SDO from the Earth in meters where “D” is radial distance along the Sun-Earth line, “W” and “N” are in the same direction as solar disk images when orientated in the normal way with solar north to the top of the image. “GHG” stands for Geocentric HelioGraphic. These coordinates are convenient for finding the nearness of the Earth to the AIA field of view (FOV) before and after actual Earth transits of the Sun wrt SDO. A simple calculation gives the distance from Earth, with atmosphere if desired, for the full FOV of AIA. This way one can determine when a coronal off-limb feature may be altered by passing through the Earth’s atmosphere. The FDS provided Earth transit times do not show times when the path of the Earth almost passes over the Sun’s limb. We do not show the FOV distance for all time steps because for almost all cases it is quite not interesting. It is however interesting to plot, in 3-D perhaps, the path of SDO about the Earth. We leave this as an exercise for a student.

One possible side benefit for having these coordinates available for the full mission is that the production processing for HMI level 1.5 (the “observables”) whenever there was missing level-1 data preventing calculation of the e.g. magnetograms or Dopplergrams almost none of the time changing keywords were calculated. Sometimes it is interesting to know where SDO was when we have no data.

References

Urban, S.E. and Seidelmann, P.K., eds, Explanatory /supplement to the Astronomical Almanac, 3rd edition, 2013.

Franz, M. and Harper, D., Heliospheric Coordinate Systems, Corrected Version of Planetary & Space Science, 50, 217ff (2002), March 13, 2017.

Archinal et al. (2011):

Carrington, R. , Observations of the Spots on the Sun, 1863

1974 American Ephemeris and Nautical Almanac

G, Davies et al., 1980.
Commission 4 in 1979
along with statements that the changes suggested in 1976 were being adopted.

Appendix

Python code for AIA FOV calculation. This code is extracted from a modules where GHGD_OBS, GHGW_OBS, and GHGN_OBS were available in arrays Coords.GHGD, Coords.GHGW, Coords.GHGN of length Coords.length, In km versus the meters in the keywords.

AIAwarn is True when the nearest with atmosphere limb of the Earth is in the AIA FOV

```
import numpy as np
atmos=100   # up the user to decide how thick the unwanted atmosphere is
rEarth = 6378 + atmos # km, plus atmosphere
AIA_FOV = 0.6 * 2048 / 3600  # 0.6 arc-sec pixels at edge of FOV in degrees
deg2rad = np.pi/180

GESNorbit = np.sqrt(Coords.GHGD**2 + Coords.GHGW**2 + Coords.GHGN**2)
# separation in degrees SDO angle from Earth center
GESNsep = np.arctan2(np.sqrt(Coords.GHGW**2 + Coords.GHGN**2) ,  Coords.GHGD)/deg2rad
 # angular size of Earth limb from SDO, degrees
gseEarthRadius = np.arctan2(rEarth , GESNorbit)/deg2rad
AIAwarn = np.ndarray((Coords.length), dtype='bool')
for i in range(Coords.length):
    AIAwarn[i] = GESNsep[i] <= (AIA_FOV + gseEarthRadius[i])
```

AIAwarn can be examined to find contiguous intervals where it is True.